Status and prospects of E336 Experiment at SLAC FACET-II on channeling plasma wakefield acceleration in structured solids

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on behalf of E336 collaboration

Channeling 2023, Riccione, 06/06/23

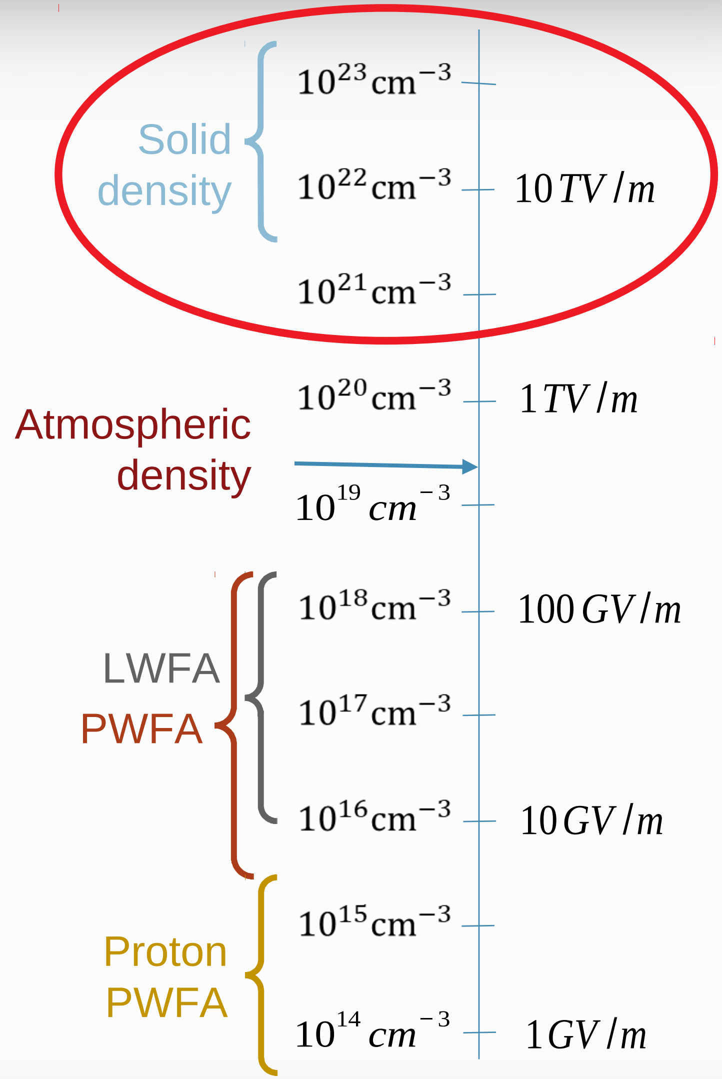
Plasma acceleration: why solid state targets?

Acceleration gradient

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

- Most PWFA/LWFA is done in ionized gas plasma sources at densities much less than atmospheric
- Solids are 4-5 orders of magnitude more dense

Solid density wakefield accelerators could produce fields of **10 TV/m**

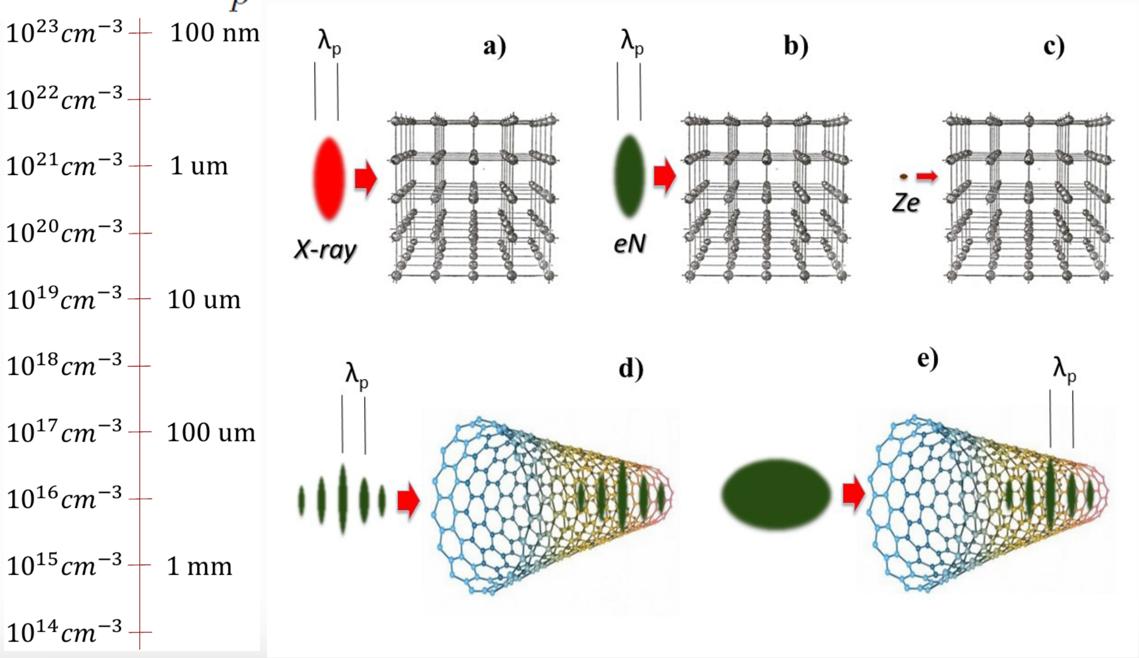


Why not amorphous targets?

Problems:

- At solid densities, scattering from plasma ions becomes significant => rapid pitch angle diffusion and particles escaping the wake
- **Transverse** and **longitudinal beam sizes** must be comparable or **smaller** than the plasma wavelength **λ_p** ,

$$\lambda_p = 2\pi \frac{c}{\omega_p}$$



Acceleration in a **nanostructure** (crystal or carbon nanotube) **limits scattering** off the solid's ions.

Periodic structure causes **transverse beam nanomodulation**

Additional pro: small beam emittance

E336 at SLAC FACET-II
Science goals and definition of success

Science goals

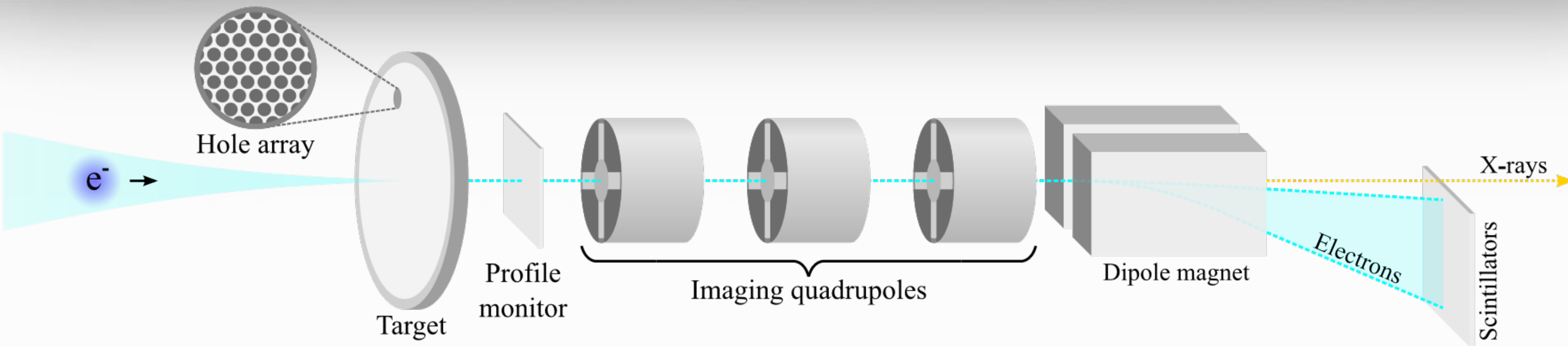
- **Proof-of-principle experiment** - demonstrate feasibility of the study of beam-nanotarget interaction and of beam-induced wakefields in nanotargets
- Observation of electron **beam nano-modulation**
- Observation of **X-ray radiation** due to transverse oscillations in wakefields
- Confirmation of **simulation models**

Definition of success:

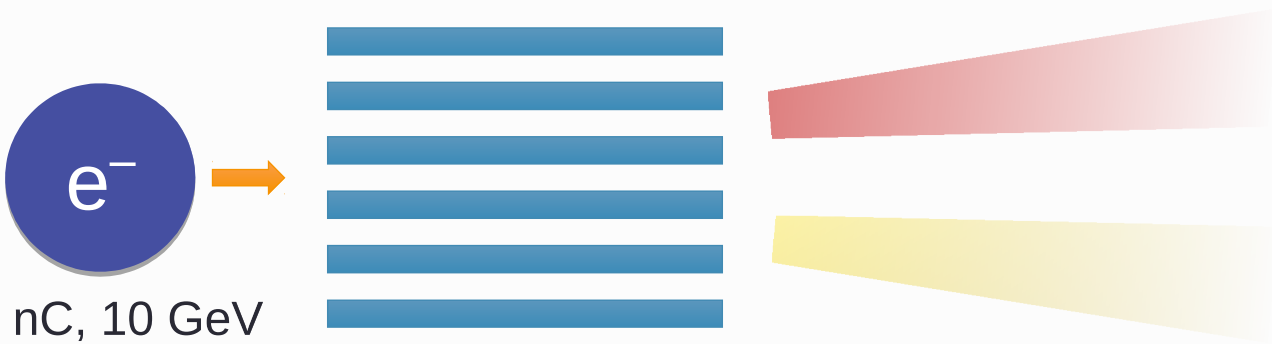
- **Evidence** for clearly distinguishable **interaction** of **FACET-II beam with structured solid targets** in comparison to amorphous targets (1.5 years)
- **Systematic parametric study** of beam-nanotarget interaction for various sample thickness, pore diameter, material type, and beam parameters, and comparison/validation against theory, to support signature and **evidence of beam nano-modulation** (3 years - dependent on beam parameters)

* R. Ariniello et al. arXiv:2203.07459 submitted to JINST

E336 SLAC FACET-II experimental setup



To measure:



2 nC, 10 GeV
1-10 µm

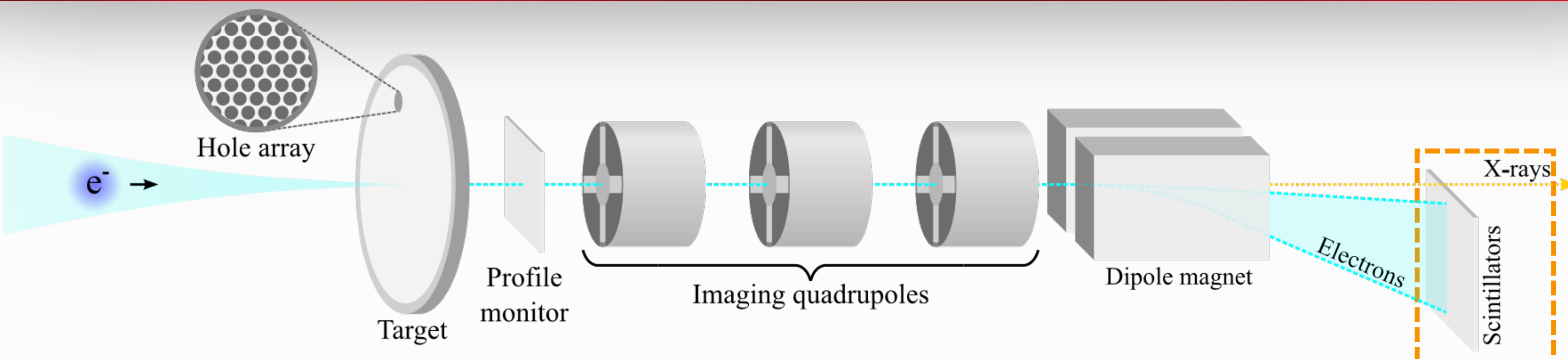
Structured target

Transverse momentum distribution & other beam parameters

X-rays
Gamma-rays

Observation of transverse plasma waves

E336 SLAC FACET-II Diagnostics and observables

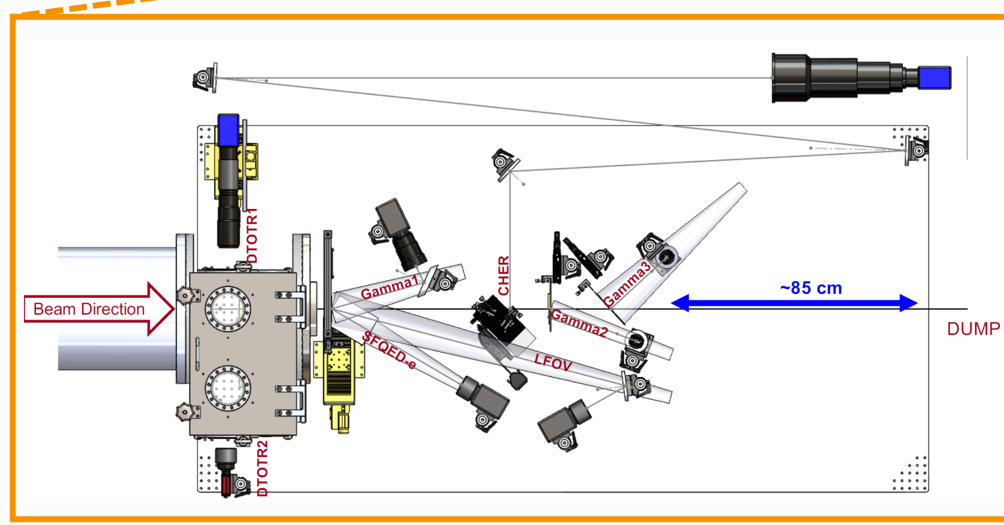


Observables

- Growth in transverse momentum spread
- Beam kicks from tilted targets
- X-rays and gamma-rays

Diagnostics

- High resolution in vacuum OTR
- A selection of gamma detectors



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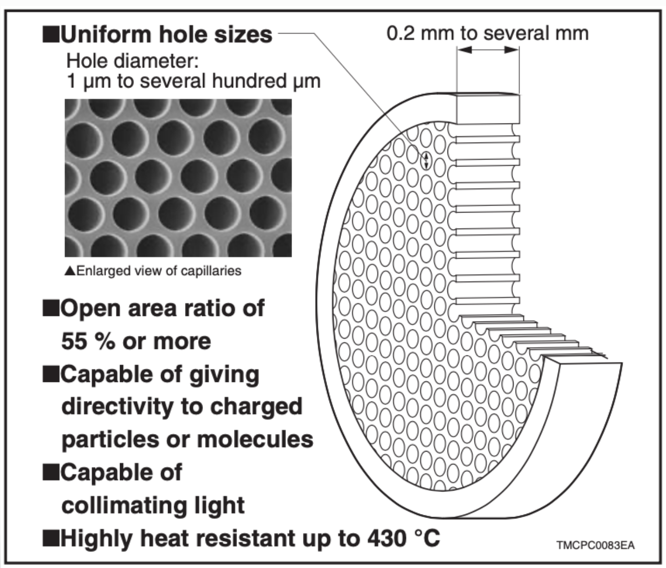
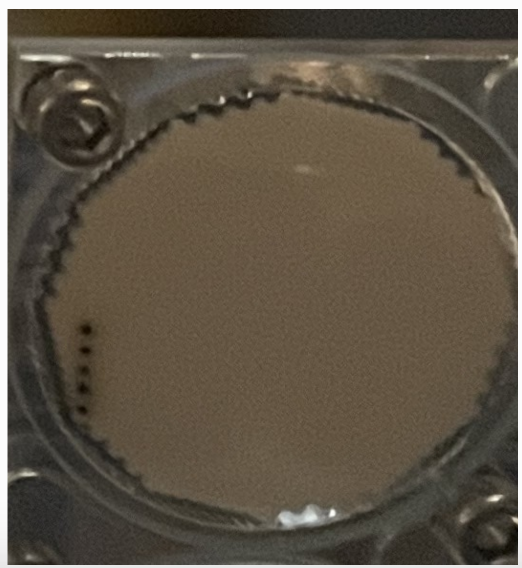
E336 SLAC FACET-II target and initial progress

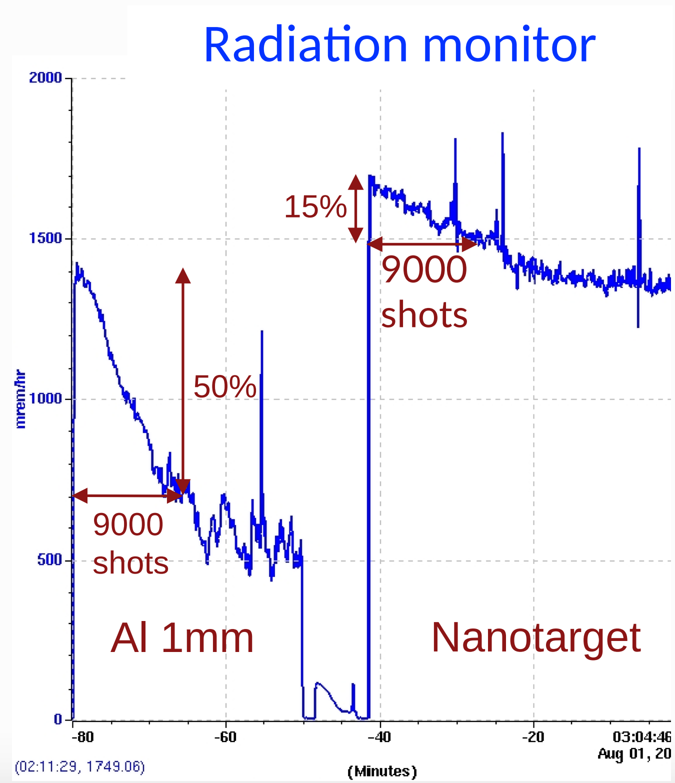
Observables

- 1 mm thick, 6 micron-diameter tubes in lead glass
- Radiation monitor downstream – drop tells how quickly the target is being damaged/drilled
- X-rays and gamma-rays

Damage observed, but targets relatively robust: 15% decrease in radiation in 9000 shots



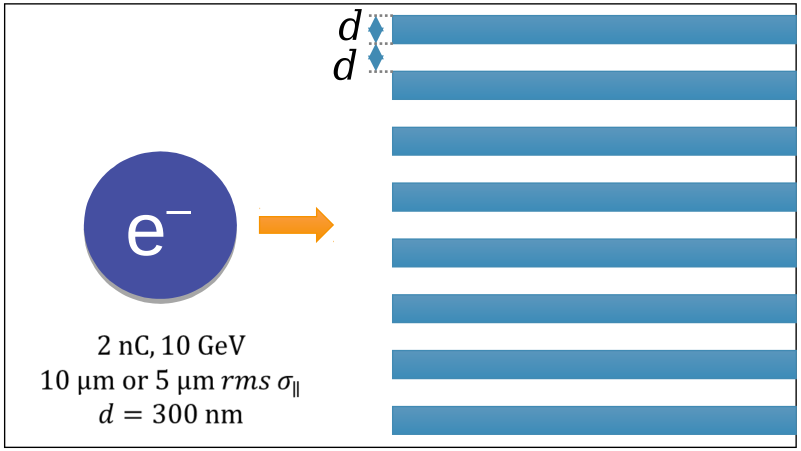


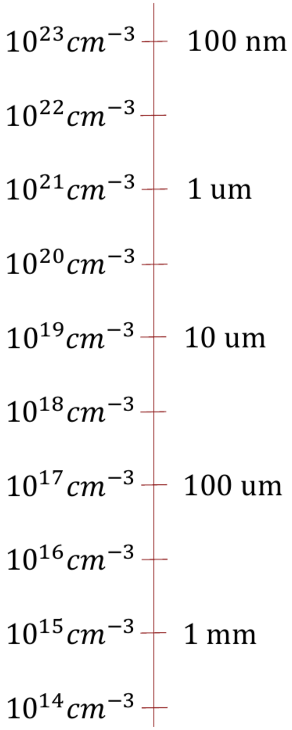


* R. Ariniello et al. arXiv:2203.07459 submitted to JINST

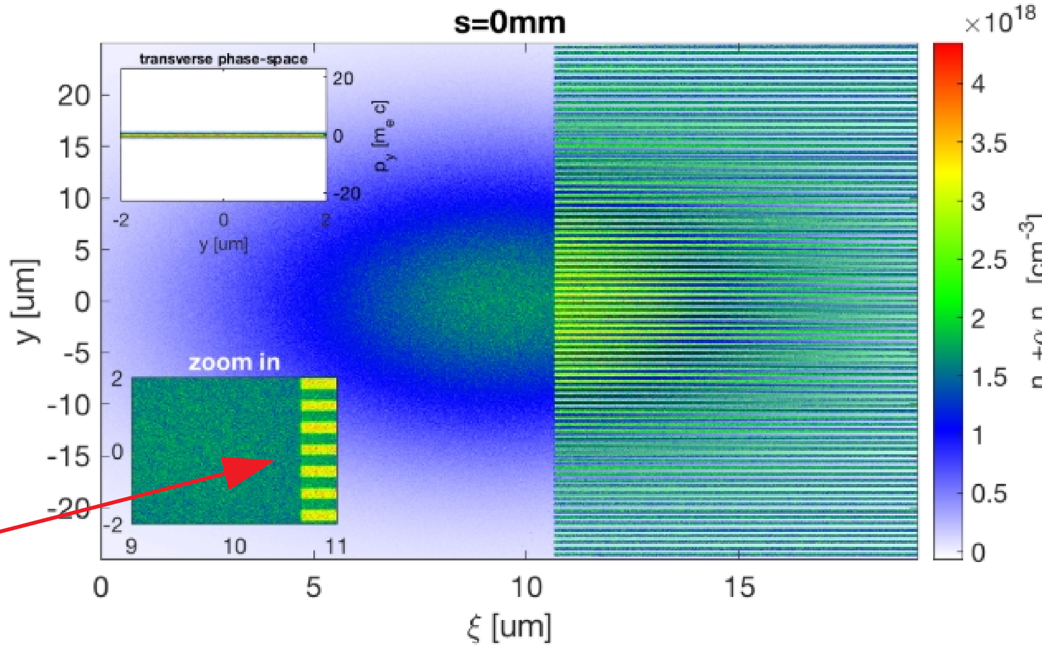
Simulation results: self-modulation of the electron beam

- **Size** of the **wake** scales as $\lambda_p = 2\pi \frac{c}{\omega_p}$
- **Driver** needs to have spatial scale on the order of the **wake scale**
- For solid densities, this is **difficult to achieve** with current facilities



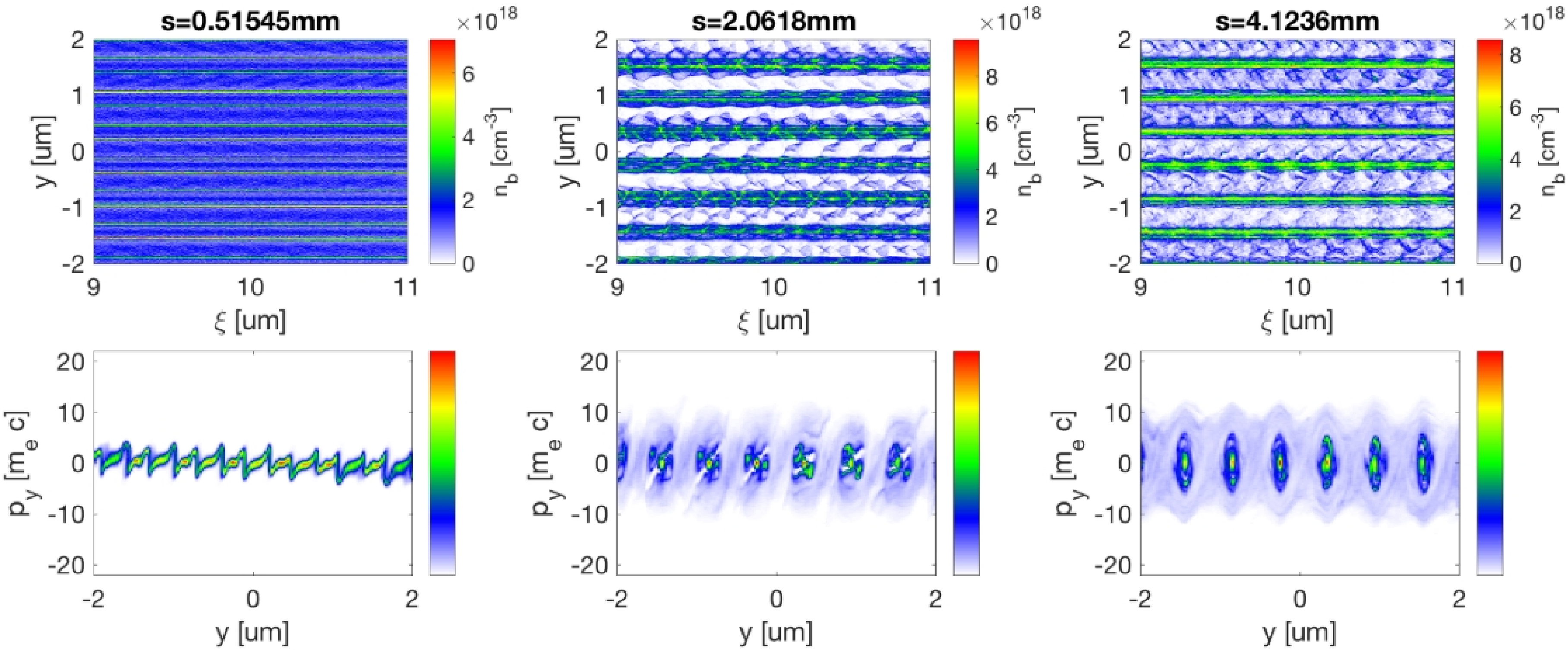


Plasma density has the same structure as the nanotarget



Simulation results: self-modulation of the electron beam

Transverse plasma waves



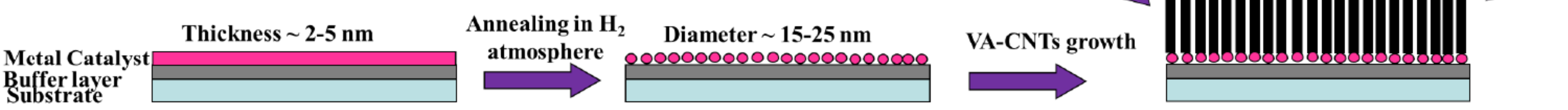
Don’t need a small driver! Imprint the target structure on the drive beam

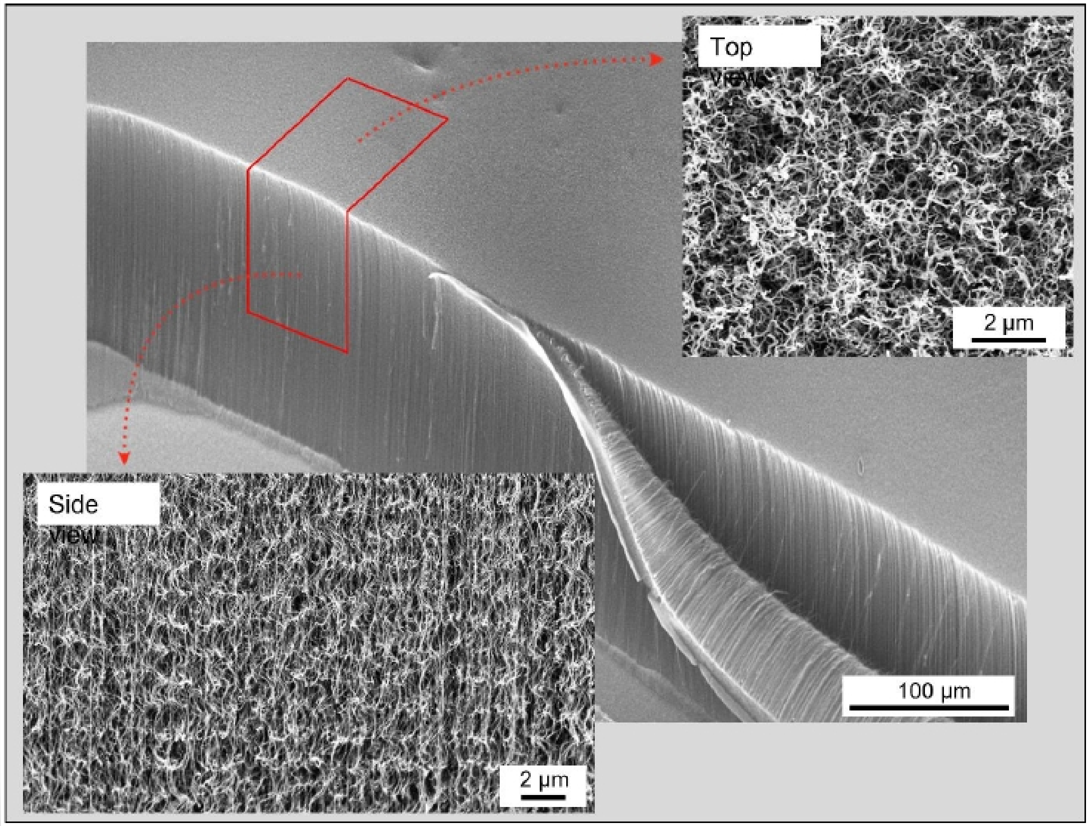
Another reason why we need nanostructures but not amorphous material

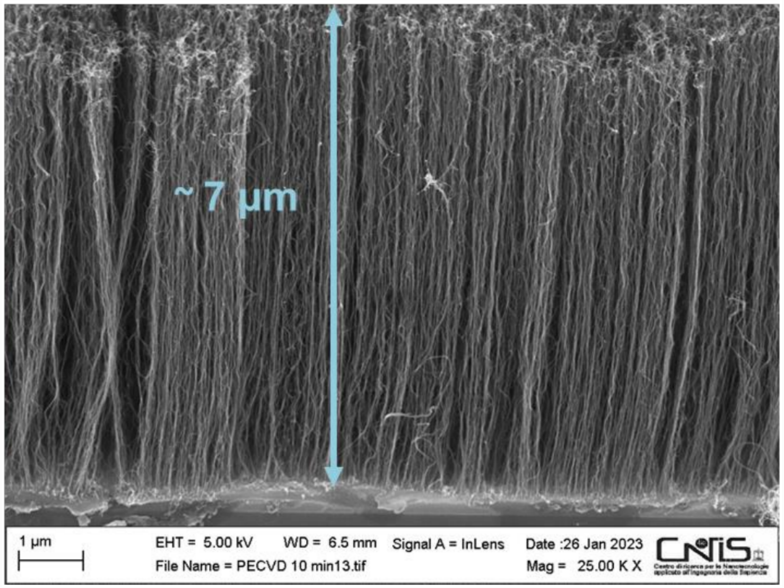
* R. Ariniello et al. arXiv:2203.07459 submitted to JINST

Future target: carbon nanotubes

Thermal decomposition of a gaseous precursor on catalytic nanoparticles in a high-vacuum reaction chamber





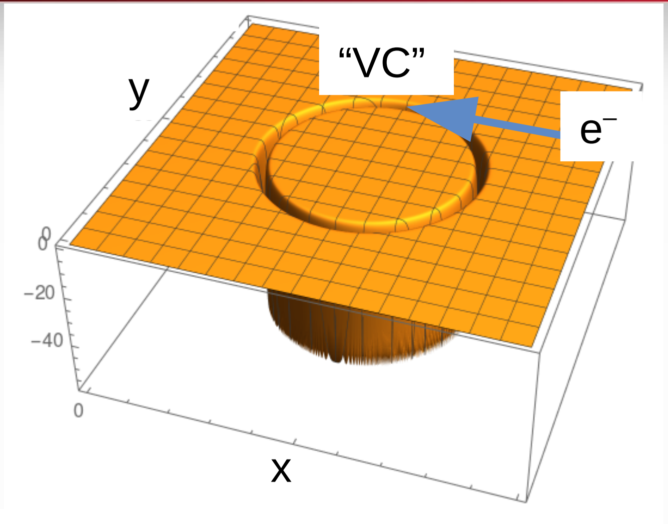


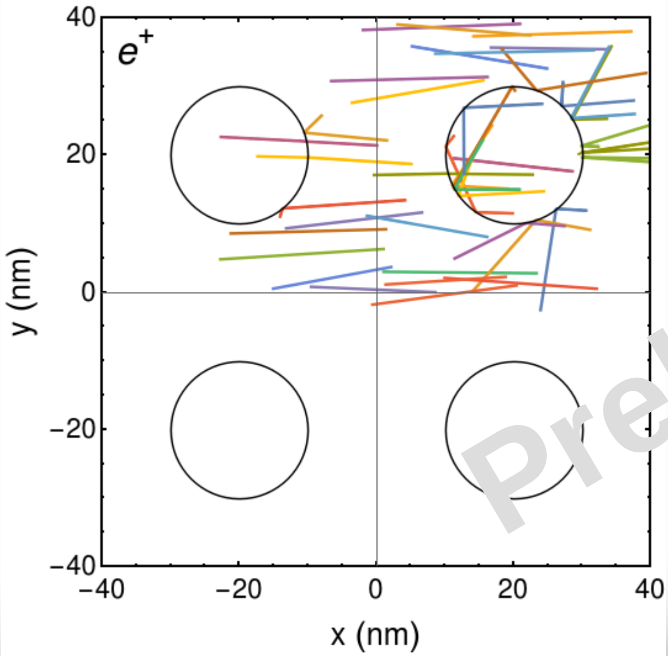
Courtesy of
Prof. Gianluca Cavoto,
Dr. Ilaria Rago

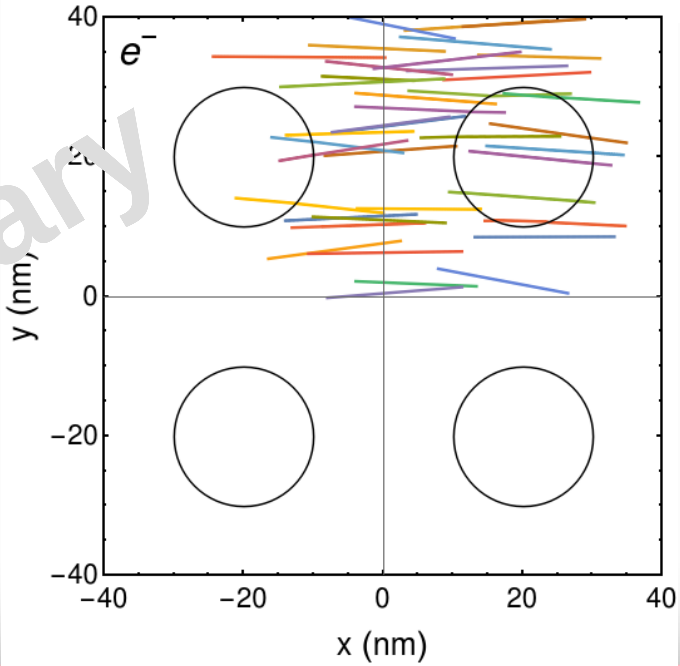
Channeling simulations in CNT: trajectories, ideal case

Simulations with **CRYSTALRAD** simulation code*

Simulation parameters:
Beam: e^-/e^+
Divergence: 10 μrad
CNT diameter: 20 nm
CNT length: 0.2 mm

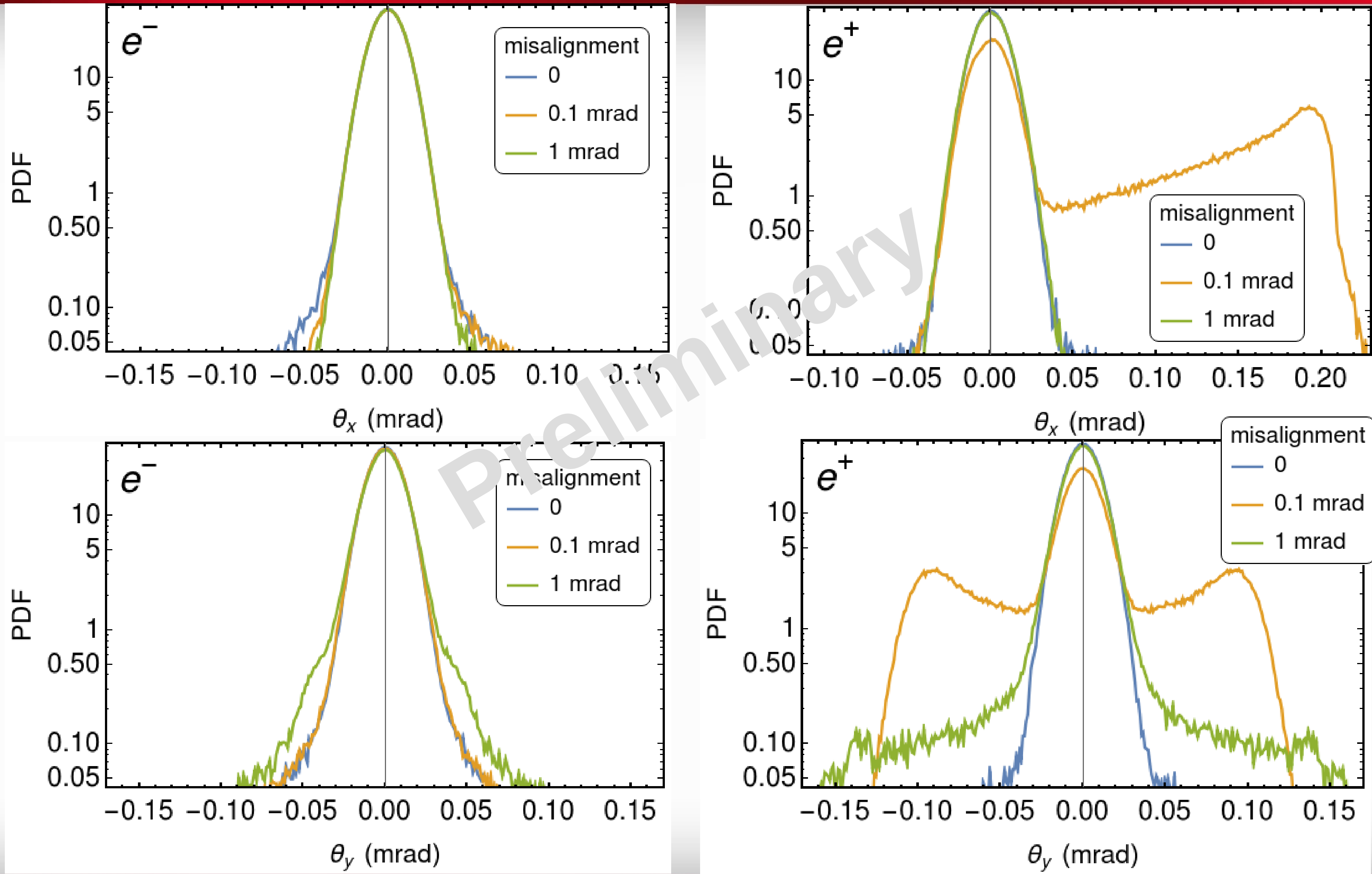






*A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Channeling simulations in CNT: angular distributions of deflected beam, ideal case

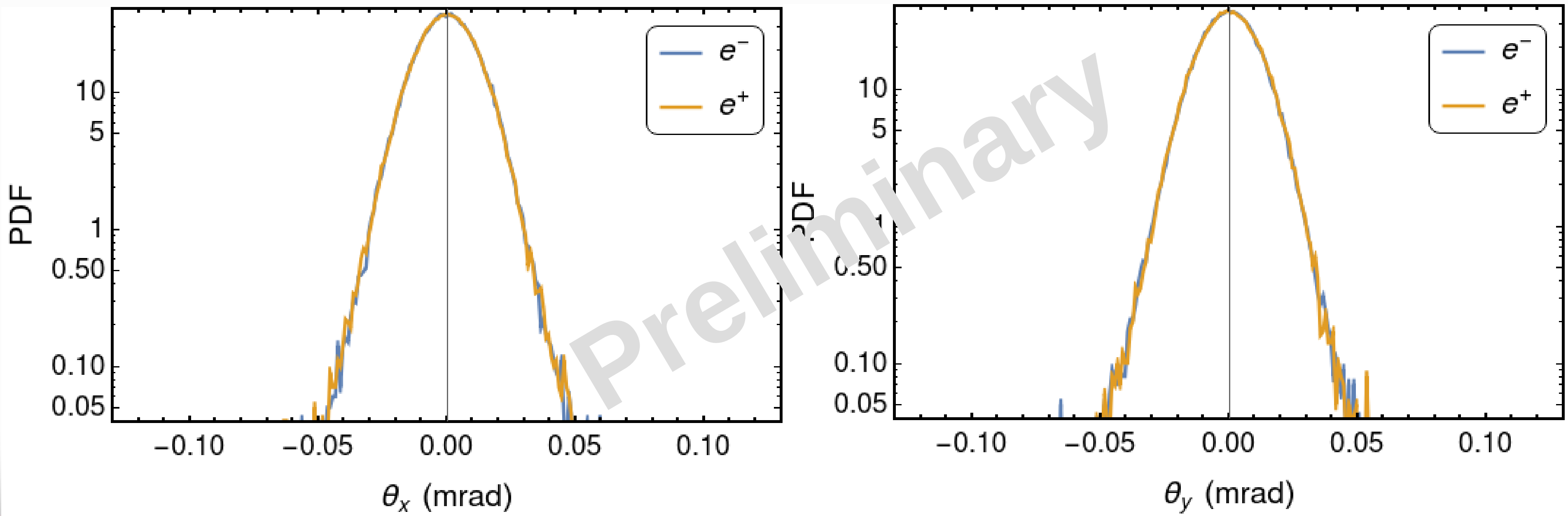


Channeling simulations in CNT: angular distributions of deflected beam, more realistic case

Simulation parameters:
"Random forest" of nanotubes with the angular misalignment 1 mrad/100 nm along the nanotube.

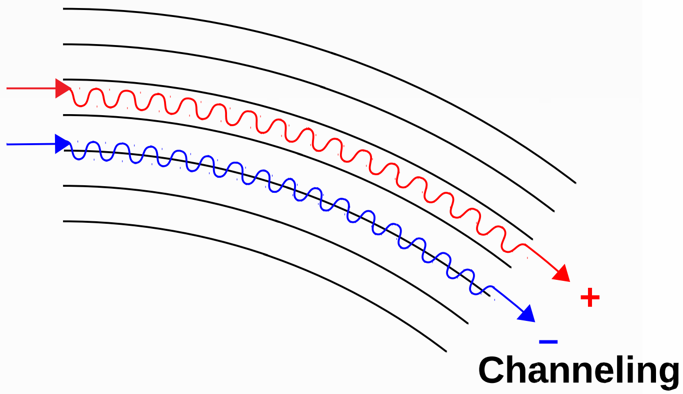
Desirable for plasma acceleration but still **not realistic.**
Real misalignment is degrees/100 nm

No traces of **coherent effects**
but
r.m.s angle = 10.9 μrad
(compare with 10 μrad of initial angular divergence)
Multiple scattering increased.

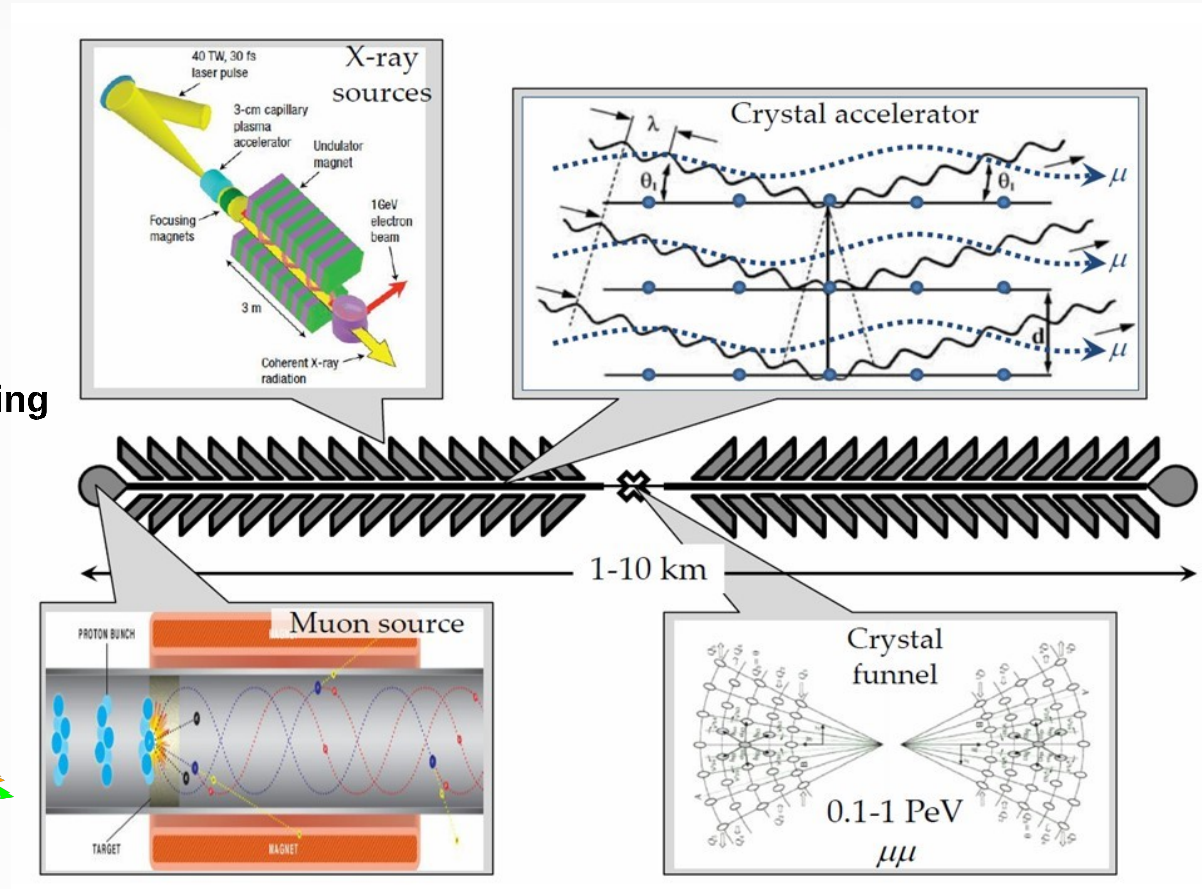


Let's dream about future lepton colliders!

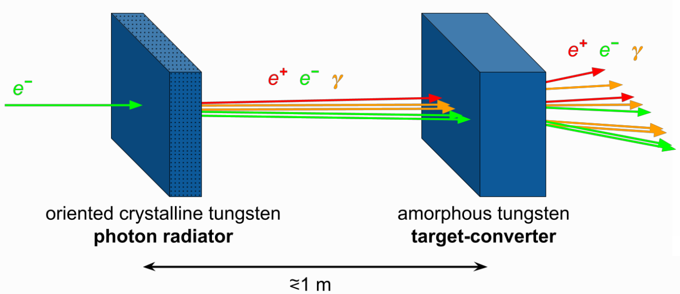
Channeling in a bent crystal



Concept of a linear X-ray crystal muon collider*,**



Hybrid crystal-based positron source**



***L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)

**V. Shiltsev, Physics-Uspekhi 55, (10), 965 (2012)

*R. Ariniello et al. arXiv:2203.07459 submitted to JINST

Conclusions

- **Plasma wakefield acceleration** at solid densities has the potential to produce **TV/m fields**.
- **Nanostructures** are required to **limit** the **beam ion scattering**.
- Also naturally channel the beam leading to **small natural emittances**.

- Driving the wake requires a beam with spatial scales on the order of $\lambda_{p.}$
- It is possible to experimentally explore the physics with current facilities by taking advantage of **self modulation in nanostructures**.
- E336 experiment aims to detect **evidence** of **beam-induced wakefields in nanotargets**

- **Next step** to explore: **carbon nanotubes** with a diameter of few tens nm.

The E336 collaboration

Collaboration and institutions:

- **IP Paris/LOA**: Sébastien Corde, Max Gilljohann, Yuliia Mankovska, Pablo San Miguel Claveria, and Alexander Knetsch
- **UC Irvine**: Peter Taborek and Toshiki Tajima
- **Fermilab**: Henryk Piekarz and Vladimir Shiltsev
- **SLAC**: Robert Ariniello, Henrik Ekerfelt, Mark Hogan, and Doug Storey
- **CEA**: Xavier Davoine and Laurent Gremillet
- **IST**: Bertrand Martinez
- **INFN**: Alexei Sytov (also in KISTI), Laura Bandiera and Gianluca Cavoto

Publications:

- White paper for Snowmass in AF6 Advanced Accelerator Concepts arXiv:2203.07459, submitted to JINST

Channeling Acceleration in Crystals and Nanostructures and Studies of Solid Plasmas: New Opportunities

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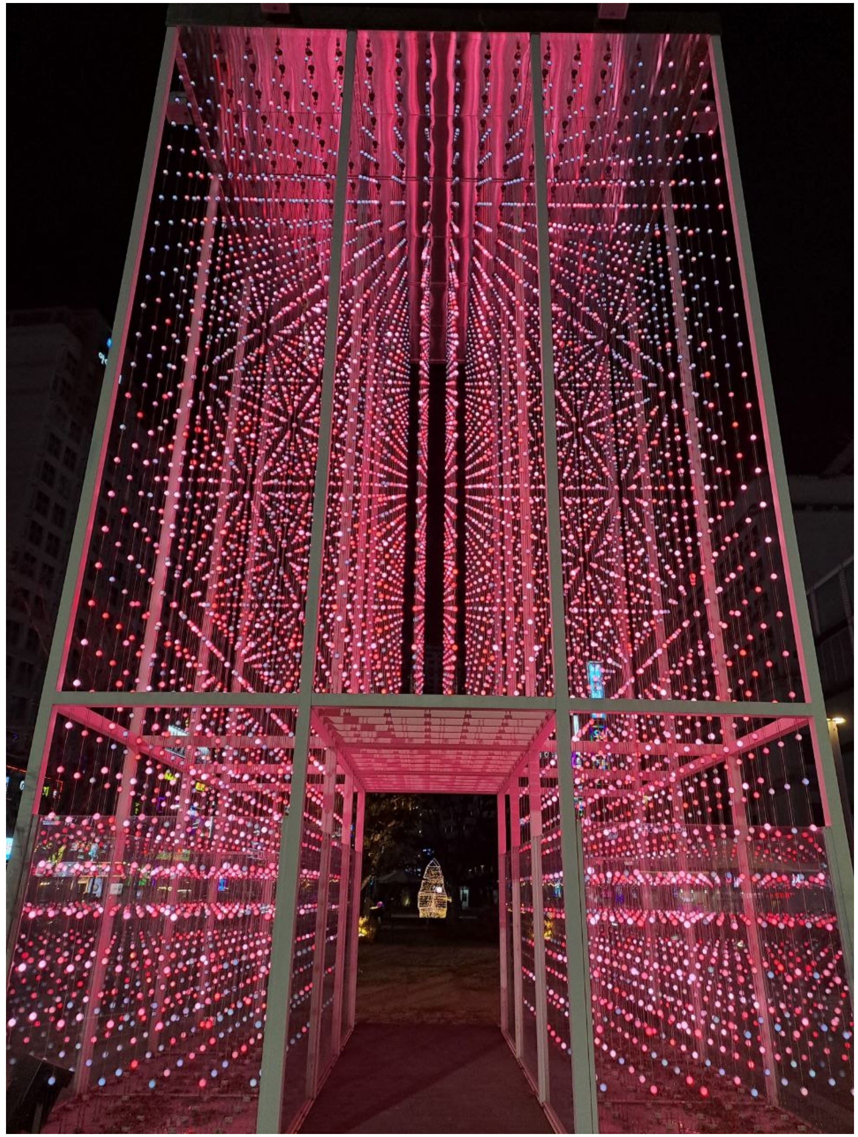

Thank you for attention!